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## 2012 International Symposium on Safety Science and Technology Experimental study on mechanism of the water-insoluble heavy gas diluted with water curtain

GUO Weiwei<sup>a,b</sup>, YUE Taotao<sup>a,b</sup>, WANG Ruizhi<sup>a,b</sup>, HUA Min<sup>a,b</sup>, LIU Yi<sup>c</sup>, JIANG Zhenglin<sup>d</sup>,  
PAN Xuhai<sup>a,b,\*</sup>

<sup>a</sup>*Institute of Fire Science and Technology, Nanjing University of Technology, Nanjing 210009, China*<sup>b</sup>*Jiangsu Key Laboratory of Urban and Industrial Safety, Nanjing 210009, China*<sup>c</sup>*Mary Kay O'Conner Process Safety Center, Texas A&M University, College Station 77843-3122, USA*<sup>d</sup>*The Fire Bureau of Jiangsu Province, Nanjing 210013, China*

### Abstract

Water curtain could dilute leaking poisonous gas or obstruct the diffusion of the poisonous gas to the sensitivity regions safely, efficiently and quickly. So it was very important to understand diffusion mechanism of the heavy gas diluted by water curtain and explore pattern of the effect of water curtain's setting parameter on the diffusion capacity of heavy gas diluted with water curtain. In this paper, experiments of fan water curtain and cone water curtain diluting CO<sub>2</sub> in open space were done. According to experiment results, dilution mechanism of fan water curtain and cone water curtain were obtained. The protective screen formed by fan water curtain could obstruct heavy gas diffusion effectively, and fan water curtain could also disperse heavy gas upwards through the mechanical effect. Cone water curtain would atomize the water and mix the heavy gas and air intensively with the help of air entrainment to dilute the heavy gas clouds. On this basis, it was concluded that when water curtain was opened before heavy gas passed through water curtain and the cone water curtain was installed in front of the fan water curtain, dilution effect was better. When water curtain was opened after heavy gas passed through water curtain and the fan water curtain was installed in front of the cone water curtain, dilution effect was better.

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**Keywords:** Safety engineering; fan water curtain; cone water curtain; heavy gas; dilution mechanism

### 1. Introduction

It was critical to prevent and mitigate water-insoluble heavy gas release. Water curtain was usually inexpensive, simple and reliable equipment [1-4] to be used in accident. It had been recognized as an efficient technique to control and mitigate various heavy gases in the process industries. The property of water curtain depended on its own characteristics and external factors. There were two types of water curtain nozzles. One was fan water curtain nozzle and the other was cone water curtain nozzle. And different water curtain nozzles had different dilution mechanism. Therefore, it was important to understand different dilution mechanism of water curtain for optimizing water curtain system settings and guiding fire engineering designs. Morshed [5-6] concluded the different characteristics of the two nozzles. Droplets of fan water curtain had large droplet size (from 3mm to 1.25mm), which led to fan water curtain had strong continuity. But the droplets of cone

\* Corresponding author. Tel.: 02583239976; fax: 02583239976.

E-mail address: [kinggww@126.com](mailto:kinggww@126.com)

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water curtain was small (drops size was from 1.25mm to 0.25mm). Fthenakis[7-9] diluted LNG gas with different types of water curtain and summarized dilution mechanism of the water curtain through the concentration and heat variation of LNG gas. O. Isnard[10] built RED model on the basis of air entrainment equation, which could be used to calculate the volume of air entrainment. Zhang[11-12] proved the effectiveness of water curtain to dilute heavy gas cloud. But the mechanism of the water-insoluble heavy gas diluted by water curtain still was not very clear. And simple and feasible water curtain settings guide on water-insoluble heavy gas were not proposed. On basis of experimental researches, dilution mechanism of water-insoluble heavy gas diluted by different water curtain models was concluded.

## 2. Experimental study

### 2.1. Water curtain system

The water curtain system included rotor flowmeter, valves, pressure gauge, and water curtain nozzle. The water pressure was 0.2MPa; water curtain injected upwards. The parameters of nozzles were shown in Table 1.

Table 1. Nozzles parameters

Nozzle model	Flow coefficient	Extending angle
Fan water curtain ZSTM-15A	35	$160 \pm 10^\circ$
Cone water curtain ZSTWB 34/60	35	$60^\circ$

### 2.2. Gas releasing system

CO<sub>2</sub> was used as the water-insoluble heavy gas in the experiment. The CO<sub>2</sub> concentration was 99%, which was packed in the 40L steel cylinder with the pressure of 10.0MPa. The gas cylinder connected with pressure reducing valve at the exit, and pressure reducing valve connected with external gas flowmeter. The outlet diameter of pipe was 6 mm and the gas leakage direction was the same as ground level.

### 2.3. Data collection

Data collection system was formed by Infrared CO<sub>2</sub> concentration sensor, transmitter, data acquisition instrument and computer data processing system. Six CO<sub>2</sub> concentration sensors were installed downwind at No.1 test point(x=6m, y=0m, z=0.3m), No.2 test point(6, 0, 0.6), No.3 test point(6, 0, 0.8), No.4 test point(8, 0, 0.3), No.5 test point(8, 0, 0.6), and No.6 test point(8, 0, 0.8) respectively(x referred to the distance from test point to leakage source along the wind direction; y referred to the distance from test point to wind direction; z referred to the height from test point to ground).

### 2.4. Initial condition

The ambient temperature was  $20 \pm 5^\circ\text{C}$ . It was sunny. Wind speed was 0-0.5m/s. CO<sub>2</sub> leakage flow rate was 6m<sup>3</sup>/h. The height of leakage source was 1.2m. Water curtain was located between leakage source and test points at the distance of 2m.

## 3. Analysis and discussion of experimental results

### 3.1. Comparison between fan water curtain and cone water curtain

#### 3.1.1. Water curtain was opened at 0s

Water curtain was opened when the heavy gas leaked. Variation diagram of the CO<sub>2</sub> concentration ( $10^{-6}$ ) with time at the six test points behind the fan water curtain was shown in Fig 1(a)(Y-axis referred to difference between CO<sub>2</sub> concentration at the six test points and in air). Fig 1(b) referred to variation diagram of the CO<sub>2</sub> concentration ( $10^{-6}$ ) with time behind the cone water curtain. And average value of the CO<sub>2</sub> concentration ( $10^{-6}$ ) was shown in Tab 2. The conclusion could be obtained from Fig 1(a) and Fig 1(b) that the concentration at the downwind of the fan water curtain was lower than that at the downwind of the cone water curtain and was fluctuated around a stable value. But the CO<sub>2</sub> concentration at the

downwind of the cone water curtain had a rising trend. Droplets of fan water curtain were large and had strong continuity, and the extending angle of fan water curtain was so big that a protective screen could be formed to obstruct most of  $\text{CO}_2$  effectively. While droplets of cone water curtain were small and had larger porosity, and the cone water curtain's extending angle was also smaller, therefore, it was easy for  $\text{CO}_2$  to penetrate core water curtain, leading to the concentration at the downwind of the cone water curtain was higher and had a rising trend.

It was shown in Fig 1(a) and Tab 2 that when  $\text{CO}_2$  dispersed freely, the concentrations at each test point changed from  $1008.435 \times 10^{-6}$  to  $3500.315 \times 10^{-6}$ . When test point positions were lower and the distance from test points to leakage source was closer, the concentration was higher. And when fan water curtain and cone water curtain were opened, the concentration at each test point changed from  $35.249 \times 10^{-6}$  to  $388.437 \times 10^{-6}$ , which showed that fan water curtain or cone water curtain could dilute heavy gas clouds diffusion effectively. When fan water curtain was opened, with the distance from test point positions to the ground becoming higher, the concentration became higher. When cone water curtain was opened, the lower the test point positions were, the higher the concentration behind the water curtain was, which resulted from that the droplets of the fan water curtain were larger and droplets themselves drove gas upwards through the mechanical effect so that the concentration was higher at the higher point. The extending angle of the cone water curtain was small so that part of  $\text{CO}_2$  penetrated at the bottom of water curtain, leading to higher concentration at lower test point. And the droplets of the cone water curtain were smaller and capacity of air entrainment was large so that  $\text{CO}_2$  and air were mixed intensively. Because of this, the concentration at the different height downwind was almost the same.

Table 2. Average value of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) behind the water curtain

Test points	No.1	No.2	No.3	No.4	No.5	No.6
No water curtain	3500.315	2697.185	2016.877	2629.068	1771.56	1008.435
Fan water curtain	102.562	128.563	109.688	49.062	61.000	67.437
Cone water curtain	378.437	371.562	365.313	274.062	243.438	254.063

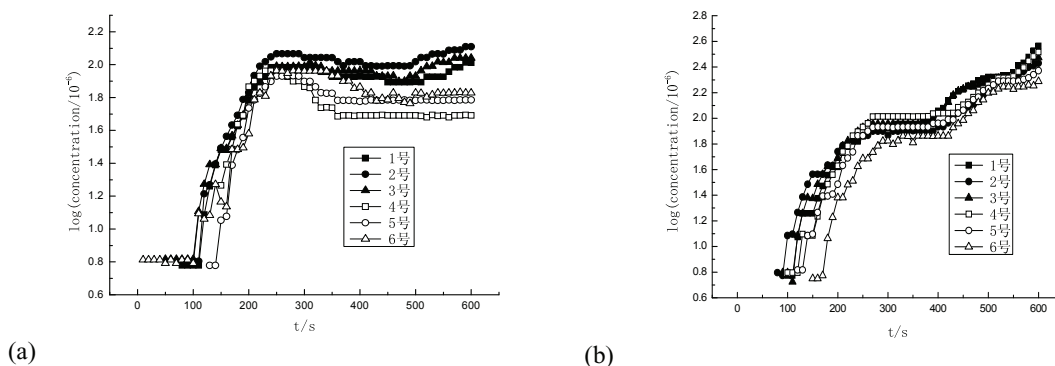


Fig. 1. Variation diagram of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) with time behind (a) the fan water curtain and (b) the cone water curtain.

### 3.1.2. Water curtain was opened at 180s

Water curtain was opened when heavy gas had leaked 180 seconds. (When  $\text{CO}_2$  had leaked 180s, the concentration reached the highest level and remained stable.) Variation diagram of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) with time at six test points behind fan water curtain and cone water curtain were shown in Fig. 2 (a) and Fig. 2 (b) respectively. It was shown in Fig. 2 (a) and Fig. 2 (b) that  $\text{CO}_2$  concentration at the downwind of the fan curtain water was higher than that at the downwind of the cone water curtain. Dilution effect of cone water curtain was better than that of fan water curtain, which resulted from that  $\text{CO}_2$  had diffused freely 180 seconds, and then there had been higher concentration. When water curtain pressure and flow coefficient were same and the droplets of water curtain became smaller, the capacity of air entrainment became larger, and the ability of dispersing heavy gas turned stronger. The droplets of cone curtain water were smaller than that of the fan water curtain, but it could entrain more air. Therefore, when  $\text{CO}_2$  had penetrated water curtain, dilution effect of cone water curtain was better than that of fan water curtain.

Average value of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) at the downwind was shown in Tab. 3. It could be seen from Fig. 2 and Tab. 3 that when  $\text{CO}_2$  diffused freely, the  $\text{CO}_2$  concentration was in line with the general laws of the heavy gas diffusion. When

fan water curtain was opened, the concentration behind water curtain decreased quickly. With the distance from test points to ground became higher, the concentration became higher. The longer distance from test points to leakage source was, the greater concentration was. When cone water curtain was opened, the concentration behind the water curtain decreased. But the concentration at each test point was almost the same. Droplets of fan water curtain drove gas upwards through its mechanical effect so that the concentration at the high point became higher. At the same time, the droplets lead to air turbulence, which dispersed  $\text{CO}_2$ . The droplets of cone water curtain were small. Therefore, cone water curtain could mix  $\text{CO}_2$  and air with the help of air entrainment, and  $\text{CO}_2$  was more evenly distributed in the space.

Table 3. Average value of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) behind the water curtain

Test points	No.1	No.2	No.3	No.4	No.5	No.6
No water curtain	3500.315	2697.185	2016.877	2629.068	1771.56	1008.435
Fan water curtain	222.125	271.813	390.248	430.876	443.068	448.188
Cone water curtain	216.25	231.875	199.688	206.876	206.562	208.437

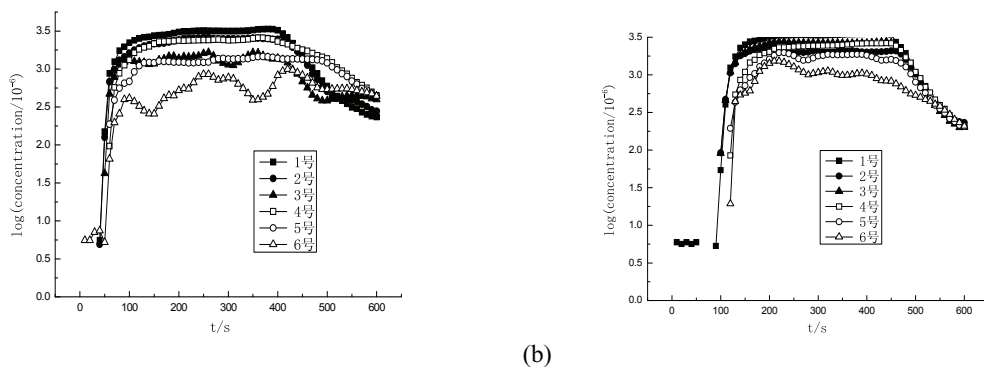


Fig. 2. Variation diagram of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) with time behind (a) the fan water curtain and (b) the cone water curtain.

### 3.2. Comparison between the fan water curtain and the cone water curtain installed in series

#### 3.2.1. Water curtain was opened at 0s

Water curtain was opened when the heavy gas leaked. Variation diagram of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) with time at the six test points behind the fan water curtain was shown in Fig 1(a) (Y-axis referred to difference between  $\text{CO}_2$  concentration at the six test points and in air). Fig 1(b) referred to variation diagram of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) with time behind the cone water curtain. And average value of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) was shown in Tab 2. The conclusion could be obtained from Fig 1(a) and Fig 1(b) that the concentration at the downwind of the fan water curtain was lower than that at the downwind of the cone water curtain and was fluctuated around a stable value. But the  $\text{CO}_2$  concentration at the downwind of the cone water curtain had a rising trend. Droplets of fan water curtain were large and had strong continuity, and the extending angle of fan water curtain was so big that a protective screen could be formed to obstruct most of  $\text{CO}_2$  effectively. While droplets of cone water curtain were small and had larger porosity, and the cone water curtain's extending angle was also smaller, therefore, it was easy for  $\text{CO}_2$  to penetrate core water curtain, leading to the concentration at the downwind of the cone water curtain was higher and had a rising trend.

It was shown in Fig 1(a) and Tab 2 that when  $\text{CO}_2$  dispersed freely, the concentrations at each test point changed from  $1008.435 \times 10^{-6}$  to  $3500.315 \times 10^{-6}$ . When test point positions were lower and the distance from test points to leakage source was closer, the concentration was higher. And when fan water curtain and cone water curtain were opened, the concentration at each test point changed from  $35.249 \times 10^{-6}$  to  $388.437 \times 10^{-6}$ , which showed that fan water curtain or cone water curtain could dilute heavy gas clouds diffusion effectively. When fan water curtain was opened, with the distance from test point positions to the ground becoming higher, the concentration became higher. When cone water curtain was opened, the lower the test point positions were, the higher the concentration behind the water curtain was, which resulted from that the droplets of the fan water curtain were larger and droplets themselves drove gas upwards through the mechanical effect so that the concentration was higher at the higher point. The extending angle of the cone water curtain

was small so that part of  $\text{CO}_2$  penetrated at the bottom of water curtain, leading to higher concentration at lower test point. And the droplets of the cone water curtain were smaller and capacity of air entrainment was large so that  $\text{CO}_2$  and air were mixed intensively. Because of this, the concentration at the different height downwind was almost the same.

Table 4. Average value of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) behind the water curtain

Test points	No.1	No.2	No.3	No.4	No.5	No.6
Fan water curtain before cone water curtain	46.249	66.813	78.125	28.126	46.251	52.500
Cone water curtain before fan water curtain	7.188	13.000	12.938	0	0	0

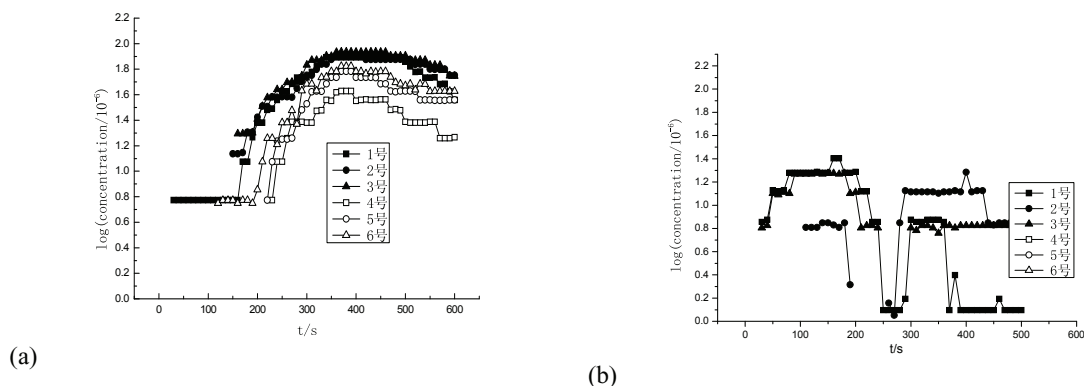


Fig. 3. Variation diagram of the  $\text{CO}_2$  concentration with time when (a) fan water curtain before cone water curtain and (b) cone water curtain before water curtain in series.

### 3.2.2. Water curtain was opened at 180s

Water curtain was opened when the heavy gas had leaked 180 seconds. Variation diagram of the  $\text{CO}_2$  concentration with time at six test points behind water curtain when the fan water curtain and the cone water curtain were installed in series was shown in Fig.4. Average value of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) at six test points behind water curtain was shown in Tab.5. It was shown in Fig.4 and Tab.5 that when fan water curtain was installed in front of cone water curtain,  $\text{CO}_2$  concentration at the downwind changed from  $115.625 \times 10^{-6}$  to  $255.938 \times 10^{-6}$ , and dilution effect was better than that of a water curtain nozzle. When cone water curtain was installed in front of fan water curtain, the concentration at the downwind was higher than that of a water curtain nozzle, and  $\text{CO}_2$  had been diffused to test point positions. When water curtain was opened, the fan water curtain ahead could obstruct leaking  $\text{CO}_2$  and the cone water curtain could dilute those  $\text{CO}_2$  which had been diffused to test point positions. So the concentration was lower than that of a single water curtain nozzle. When cone water curtain was located ahead, fan water curtain could form a protective screen to obstruct air entrainment at the rear-end boundary layer of the cone water curtain, which lead to  $\text{CO}_2$  was difficult to be diluted. For this reason, dilution effect was worse than that of a single cone water curtain.

Table 5. Average value of the  $\text{CO}_2$  concentration ( $10^{-6}$ ) behind the water curtain

Test points	No.1	No.2	No.3	No.4	No.5	No.6
Fan water curtain before cone water curtain	144.25	134.875	115.625	255.938	231.625	219.25
Cone water curtain before fan water curtain	650.50	550.69	503.75	881.94	785.31	735.69

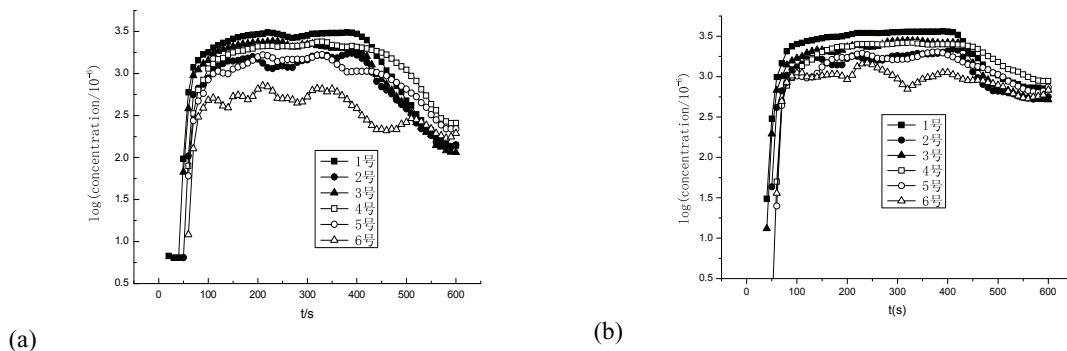


Fig. 4. Variation diagram of the CO<sub>2</sub> concentration with time when (a) fan water curtain before cone water curtain and (b) cone water curtain before water curtain in series.

#### 4. Conclusions

(1) The droplets of fan water curtain were large and had strong continuity, and its extending angle was also big, so a protective screen could be formed to obstruct diffusion of heavy gas effectively. And the droplets of fan water curtain drove heavy gas upwards through its mechanical effect. At the same time, large droplets lead to air turbulence to disperse heavy gas so that heavy gas clouds were diluted.

(2) The cone water curtain had smaller droplets, and atomized water in a larger scale, which lead to large air entrainment. So heavy gas and air could be mixed intensively, and then heavy gas clouds were diluted.

(3) Water curtain was opened when the heavy gas leaked, the dilution effect of the fan water curtain was better. Water curtain was opened when the heavy gas had leaked a period of time, dilution effect of the cone water curtain was better.

(4) Water curtain was opened when the heavy gas leaked, and when the cone water curtain was installed in front of the fan water curtain, dilution effect was better. Water curtain was opened when the heavy gas had leaked a period of time. When the fan water curtain was installed in front of the cone water curtain, dilution effect was better.

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